Reeves, et al., in Substorms 3, ESA SP-339, 187-192, 1996.

Quantitative Experimental Verification of the Magnetic Conjugacy of Geosynchronous Orbit and the Auroral Zone

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ABSTRACT

A fundamental consensus of the first International Conference on Substorms (ICS-1) was that important auroral process are related to processes in space that occur near the inner edge of the plasma sheet. Numerical magnetic field models and popular opinion suggest that the aurora in the ionosphere map magnetically to the equatorial ionosphere at distances of perhaps 6 to 10 R_E. This study tests those propositions quantitatively by comparing the predictions of five magnetic field models with measured magnetic conjunctions between low- and high-altitude satellites. The mapping is tested observationally by comparing electron energy spectra obtained by the Magnetospheric Plasma Analyzer (MPA) at geosynchronous orbit and by the DMSP spacecraft. Typically, the spectra match well for only a few seconds so the accuracy is better than one degree. We then compare the measured magnetic footpoints of geosynchronous orbit with the footpoints predicted by five magnetospheric field models: Tsyganenko-89, Tsyganenko-87, Tsyganenko-82, Oslen-Pfitzer, and Hilmer-Voigt. Based on a set of over 100 measured magnetic conjunctions we confirm that geosynchronous orbit generally has its magnetic footpoint in the auroral zone but that there is significant variation. Statistically the uncertainty in the mapping given by magnetic field models is approximately $\pm 3°$. Only about 25-30% of the time did the field model predict the conjunction to within $\pm 1°$ and as much as 20% of the time the field model could be off by more than $\pm 5°$. Although there are significant differences between the mappings predicted by various magnetic field models but that there is no clear "winner" in predicting the observed mapping. We also suggest that this technique provides an excellent opportunity for testing future magnetic field models and for determining the appropriate parameterizations for those models.

1. INTRODUCTION

A fundamental goal of substorm research is to understand the relationship between auroral processes and associated substorm phenomena observed in space. The two regions of space are connected by the earth's magnetic field and by the charged particles that can travel relatively freely along the magnetic field lines. The magnetic field lines themselves are not directly observable so our understanding of the magnetic mapping between the auroral ionosphere and the equatorial magnetosphere depends heavily on models of the earth's magnetic field.

The current generation of empirical magnetic field models (including those of Tsyganenko) are statistical fits to single point measurements of the magnetic field measured by spacecraft in the magnetosphere. The models have commonly been tested by comparing model magnetic field vectors to the magnetic field measured by one or more spacecraft in the magnetosphere (e.g. [Ref. 1], [Ref. 2], [Ref. 3], [Ref. 4], [Ref. 5], [Ref. 6]). However, tests of the magnetic field mapping are less common, more difficult, and also more sensitive because they integrate along the entire field line.

In this study we test the mapping between the auroral ionosphere and geosynchronous orbit by comparing the spectra of low energy electrons measured at both locations. While this technique has limitations it is probably the most reliable method currently available to test the magnetic *mapping* between auroral and magnetospheric substorm signatures.

2. FINDING MAGNETIC CONJUNCTIONS

The technique we use to establish magnetic conjugacy between the low- altitude DMSP spacecraft and the geosynchronous satellites is to compare electron energy spectra on the two satellites as a function of time and to look for times when the spectra are very nearly identical. DMSP orbits at an altitude of approximately 850 km in a nearly polar, circular orbit with a period of approximately 90 minutes. Therefore DMSP crosses the geosynchronous L-shell approximately once every 23 minutes. The DMSP orbits are also sun-synchronous so each DMSP satellites samples a nearly fixed region of local time.

The geosynchronous satellites orbit at a geocentric distance of 6.6 R_E with a period of 24 hours and therefore must pass through the local times sampled by the DMSP satellites. In this sense the orbits are perpendicular to each other and for each geosynchronous-DMSP satellite pair there are numerous possible conjunctions each day. To further increase the statistics we use data from two geosynchronous satellites (1989-046 and 1990-095) and from three DMSP satellites (DMSP F8, F9, and F10).

We define a "nominal conjunction" as a time when one DMSP and one geosynchronous satellite are within $\pm 10°$ in magnetic longitude and when DMSP is between 50° and 80° magnetic latitude. During a

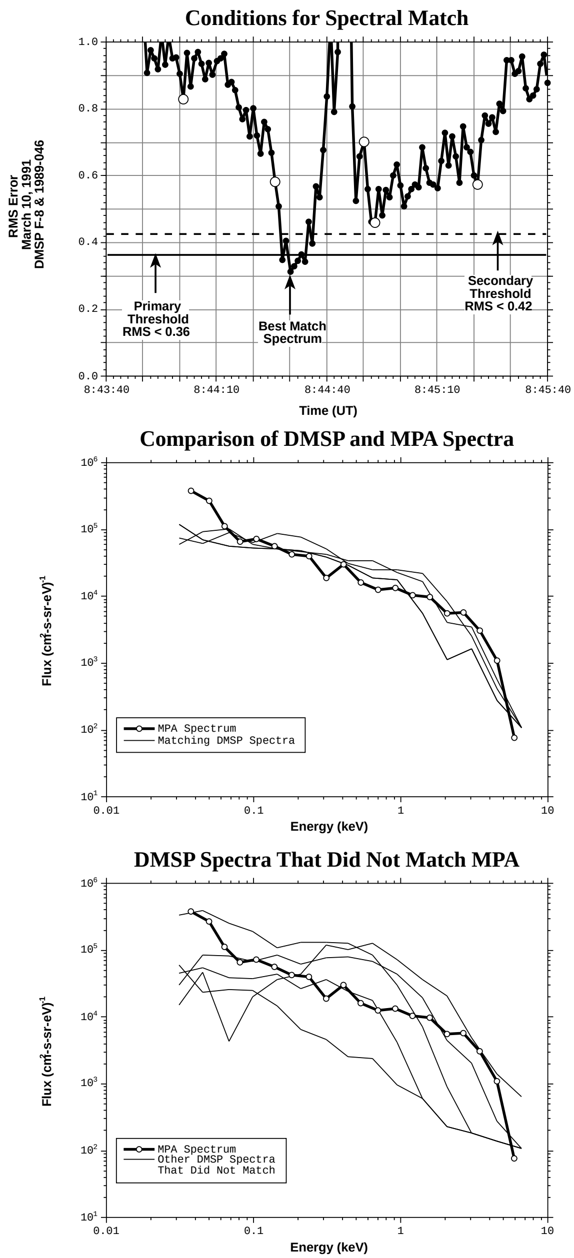


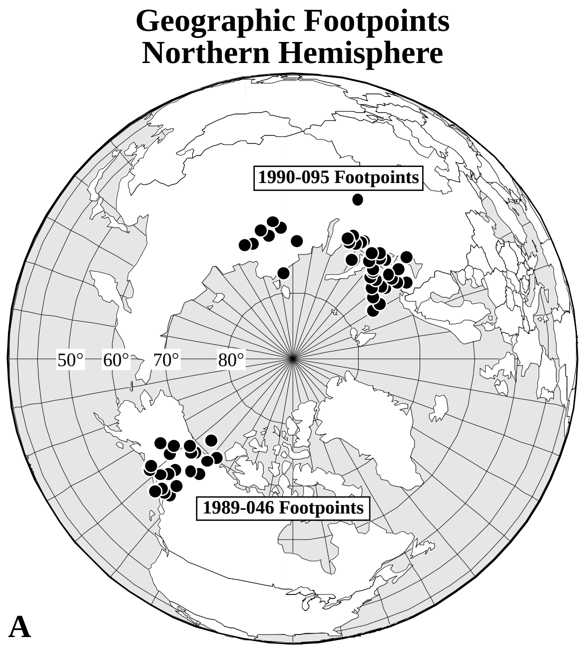
Figure 1: An illustration of how good spectral matches are chosen. The top panel shows the RMS difference between the MPA and DMSP spectra as a function of time. The second panel shows MPA and DMSP spectra that met our matching criteria for this event. The bottom panel shows several DMSP spectra in this interval that did not match the MPA spectrum. The times of those spectra are shown with open circles in the top panel.

nominal conjunction we examine the electron energy spectra from the SSJ/4 instrument on DMSP which measures precipitating electrons in 20 energy bins from 30 eV to 30 keV [Ref. 7]. One complete energy spectrum is obtained every 1 second which provides excellent resolution in latitude. At the same time we examine electron energy spectra from the Magnetospheric Plasma Analyzer (MPA) instrument at geosynchronous orbit. The MPA is a spherical-sector electrostatic analyzer which measures electrons from about 1 eV to 40 keV [Ref. 8]. The MPA measures in a fan of 6 look directions and takes 24 azimuthal sectors in each 10-second spin of the spacecraft. The spacecraft spin axis points toward the center of the earth so excellent pitch angle coverage is obtained.

In comparing spectra it is important that several conditions be met. First, since DMSP measures only that portion of the distribution that is in the loss cone we use only the geosynchronous MPA spectrum that is most nearly field aligned (as described in [Ref. 9] and [Ref. 6]). Second, our technique assumes that the magnetic field is unchanging in the time it takes DMSP to cross the geosynchronous field line so we limit analysis to times when the MPA spectrum is constant for several minutes. This criteria also assures that there are not strong variations in local time in the vicinity of the geosynchronous spacecraft. Finally, we also eliminate times when there is a field-aligned potential drop. This occurs naturally as a result of our spectral comparison because if DMSP is measuring an accelerated population and MPA is not then the spectra will not match. We assure this by adopting an extremely strict condition for spectral matching.

Figure 1 shows a typical spectral match and the criteria used to define it. In the top panel we plot the RMS difference between the spectrum measured by DMSP and by MPA for two minutes of a nominal conjunction. We define a "measured conjunction" as the times at which the RMS difference in the spectra falls below a threshold of 0.36. By examining a large number of spectra we determined that this threshold is actually more selective than a visual examination of the spectra. Furthermore we require that a measured conjunction last for less than 30 seconds. This assures that the longitude range over which the spectra match is sufficiently small that we can distinguish between one magnetic field model and another. Finally, we also require that the RMS error does not fall below a second threshold of 0.42 for more than 60 seconds which assures that the minimum in the RMS is sharp and well-defined.

In this case our "measured conjunction" (as defined by the criteria above) lasted for 6 seconds. The middle panel in Figure 1 shows the MPA spectrum and DMSP spectra that satisfied our matching criteria. (We note that the energy spectra use the nominal calibrations of the instruments and are not normalized in any way.) In the bottom panel of Figure 1 we plot the same MPA spectrum along with 5 other DMSP spectra. The times of those spectra are marked with open circles on the RMS plot in the top panel. Clearly the spectral match for those times is significantly worse. We also point out that this is only a 2-minute portion of the DMSP crossing which occupies a very small portion of a typical



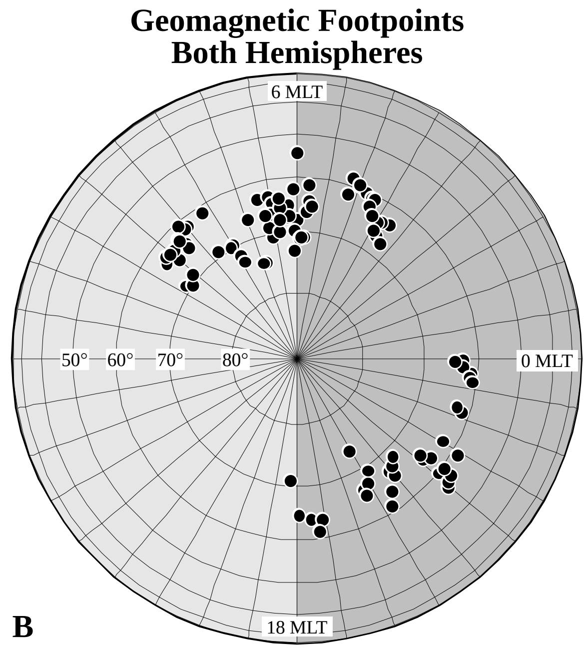


Figure 2: The location of DMSP when it measured a magnetic conjunctions with a geosynchronous satellite. (A) The position of DMSP in geographic coordinates. Only northern hemisphere conjunctions are shown. (B) The position of DMSP in geomagnetic coordinates (magnetic latitude and magnetic local time). Conjunctions from both hemispheres are shown.

DMSP spectrogram plot. Outside this 2-minute interval the DMSP spectrum did not even resemble the MPA spectrum which is what one would expect since during those times DMSP is mapping to very different parts of the magnetosphere.

This type of two-point spectral comparison has been used before to establish magnetic conjugacy ([Ref. 10], [Ref. 11], [Ref. 12], [Ref. 13], [Ref. 14], [Ref. 15], [Ref. 16]). What distinguishes this study from earlier studies is that we have established an automated algorithm for identifying magnetic conjunctions and we have applied it to a set of satellites that have frequent conjunctions. This allows us to study the magnetic mapping from geosynchronous orbit to the ionosphere in a statistical manner.

3. MEASURED CONJUNCTION STATISTICS

Using the technique described in the previous section we examined three months of data (March, September, and December, 1991) for nominal conjunctions between one of three DMSP satellites (F8, F9, and F10) and one of the two geosynchronous satellites (1989-045 and 1990-095). Out of over 3,500 nominal conjunctions we found 102 that satisfied our selection criteria. For each of the 102 conjunctions we identified the times of all spectra that met our criteria as well the single 1-second DMSP spectrum that best matched the MPA spectrum (as defined by the minimum RMS error).

Figure 2 shows the location of DMSP at the times when the best matched spectra were observed. Figure 2a shows DMSP's geographic location (for Northern hemisphere conjunctions) and Figure 2b shows its location in magnetic local time and magnetic latitude (for Northern and Southern conjunctions). Because we are using geosynchronous satellites we are limited to the geographic longitudes those satellites sample. 1989-046 had footpoints near Alaska. 1990-095 has two clusters of footpoints – over western and central Russia – because it was moved in the middle of 1991. Likewise, because the DMSP satellites are sun-synchronous they sample only a limited range of local time. But, thanks to the rotation of the earth's dipole DMSP is able to sample about one half of the possible magnetic local times (see Figure 2b).

It is apparent from Figure 2 that the footpoint of geosynchronous orbit generally lies in the auroral ionosphere. Most often it is in the region of diffuse aurora but it frequently lies in the region of discrete aurora. It is also apparent from the figure that the footpoint of geosynchronous orbit can be quite variable, spreading over more than 10° in magnetic latitude. A related study [Ref. 9], investigates how well the measured location of the geosynchronous footpoint correlates with various magnetospheric indices such as Kp, AE, Dst, the local tilt of the field at geosynchronous orbit, and the equatorward edge of the auroral boundary. In this paper our emphasis is on evaluating how well various magnetic field models predict the location of the measured footpoint. An important point about Figure 2 is that no magnetic field models have been used to determine the magnetic footpoints of geosynchronous orbit. Therefore

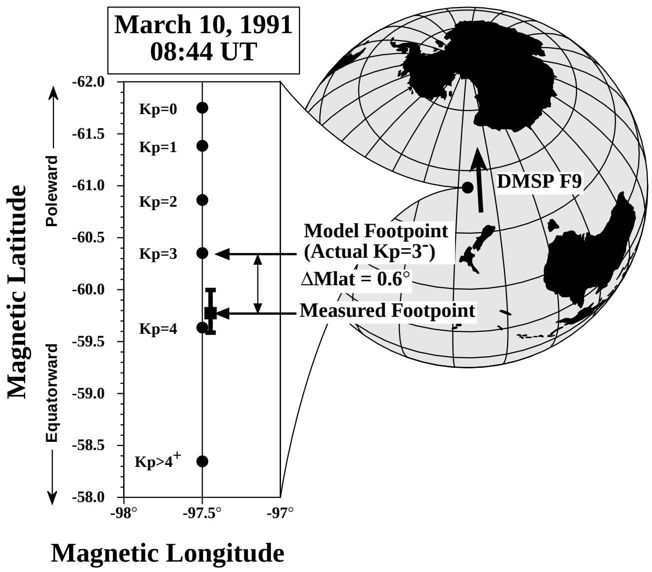


Figure 3: Comparing a the measured footpoint with the footpoint predicted by the Tsyganenko-89 model. The globe shows the location of DMSP when it measured a good spectral match with MPA. The inset shows the magnetic latitude and longitude of the measured footpoint with a bar for the location of DMSP during the entire spectral match and a square for the location of the best spectral match. The footpoints predicted by various Kp levels of the Tsyganenko-89 model are shown with circles. The actual Kp was 3^- which gives a difference for this event of only 0.6°.

we have a completely model-independent data set of field line mappings which we can use to evaluate magnetospheric magnetic field models.

4. COMPARISON WITH MAGNETIC FIELD MODELS

We now compare the magnetic field mapping determined from the DMSP and MPA spectra with the magnetic field mapping predicted by various magnetic field models. The models we use are the Tsyganenko-89 [Ref. 1], Tsyganenko-87 [Ref. 17], Tsyganenko-82 [Ref. 18], Olsen-Pfitzer [Ref. 19], and Hilmer-Voigt [Ref. 20] magnetic field models. For each of these models we use the IGRF representation of the earth's internal field. This is very important for mapping studies because, as shown in [Ref. 21], the deviation of the earth's field from a dipole can have a significant effect on the magnetic mapping from geosynchronous orbit to low altitudes.

Figure 3 illustrates the method we used to compare the footpoints predicted by the field models with the measured footpoint determined from DMSP and MPA spectra. This event is the same event shown in Figure 1. It was a conjunction between the DMSP F9 satellite and the geosynchronous satellite 1989-046. The best spectral match was recorded by DMSP at 08:44:30 UT when DMSP was at −59.78° magnetic latitude. DMSP was in the southern hemisphere moving poleward and during the 6-seconds of spectral match it moved only 0.4° in magnetic latitude.

An expanded plot of region of the conjunction is shown in the inset. Here we have plotted the location of the footpoint measured by DMSP with a square and the location of the footpoints predicted by the Tsyganenko-89 magnetic field model with circles. In both cases the footpoint is defined at an altitude of 100 km. The Tsyganenko-89 field model comes in five versions for integral values of the magnetic activity parameter Kp. For this event Kp=3^- and the Tsyganenko-89 model predicted a footpoint which was 0.6° further poleward than the actual measured footpoint which is excellent agreement.

We calculated the difference in magnetic latitude of the footpoint for each of the five models used in this study and for each of the 102 conjunctions in our data set. We used each model "as advertised". In other words, for the Tsyganenko family of field models we used the actual Kp parameter for each conjunction to specify what version of the model to use. The Hilmer-Voigt model is specified by three parameters: Dst, the stand-off distance of the magnetopause (given by solar wind pressure), and the equatorward boundary of the auroral oval (given by DMSP electron precipitation signatures). For the Hilmer-Voigt model we again used the parameters that were appropriate for each event. The Olsen-Pfitzer model has no free parameters so the same model applies to all of our cases.

A histogram of the difference between the measured and model footpoints for each of the five models is plotted in Figure 4. The top panel shows the statistics for the Tsyganenko-89 model. Here, 32% of the model footpoints agreed with the measured footpoints to within ±1°, 65% were within ±3°, and 83% were within ±5°. Put another way, if you need to know the location of the footpoint of geosynchronous orbit to within 1° the Tsyganenko-89 model has a 32% probability of being correct. However, it also has a 17% chance of being off by more than 5° and the statistical uncertainty in the mapping is ≈ 3°.

A fairly surprising result of this study is that, on average, all the field models tested perform about equally well – or equally poorly. The three generations of Tsyganenko magnetic field models contain various refinements and improvements but the changes in model did not improve the accuracy of the mapping from geosynchronous orbit to the ionosphere. This is in part because the measured footpoints have a much larger range of latitudes than is accommodated in the models. (Compare Figures 2 and 3.) However, the Tsyganenko models have a larger range than the Olsen-Pfitzer model (which has none) yet the Olsen-Pfitzer model does as good a job

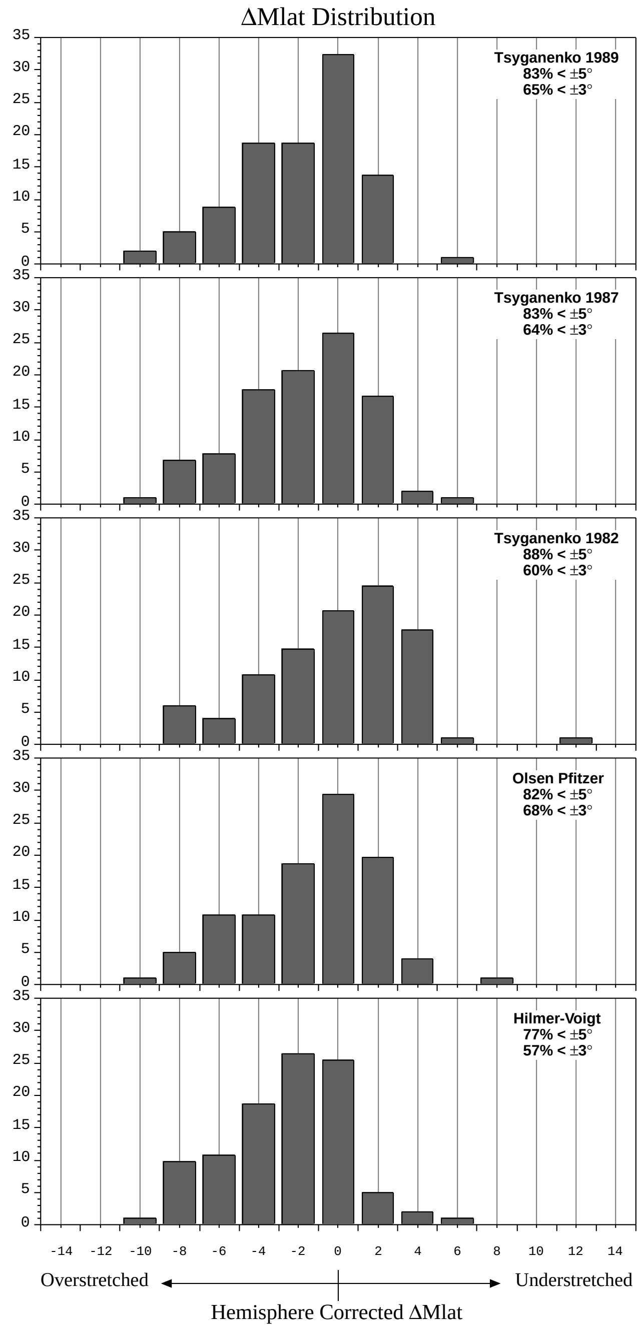


Figure 4: Histograms of the difference between the measured and model footpoints. All models share the same strengths and weaknesses (see text).

of predicting the location of the geosynchronous footpoint as any of the Tsyganenko models. This is no doubt in part because Kp is a poor parameter to use for determining the amount of stretching in the field. In fact it has been shown ([Ref. 16], and [Ref. 9]) that the Kp value needed for the Tsyganenko-89 model to reproduce the observations is completely uncorrelated with the actual Kp measured for an event. It may, then, be somewhat surprising that the Hilmer-Voigt model, which uses a set of parameters which might be expected to be better correlated with the measured footpoint of geosynchronous orbit, still does not perform significantly better than its rivals.

Finally we note that the distributions are also not symmetric. The difference in magnetic latitude is calculated such that, regardless of what hemisphere DMSP was in, negative values represent cases where the measured footpoint was poleward of the model footpoint and positive values represent cases where the measured footpoint was equatorward of the model footpoint (for example the conjunction shown in Figure 3). The more stretched the field model is the further equatorward the model footpoint moves. (See Figure 3.) Therefore negative values mean that the model is too stretched compared to the observations and positive values mean that the model is not sufficiently stretched.

It is apparent from Figure 4 that all the models are, on average, too stretched. Our cases include a variety of types of magnetospheric conditions which include quiet times, growth phases, expansion phases, and recovery phases and a variety of activity levels from Kp=0 to Kp=9^-. We note, however, that we have very few conjunctions in the midnight local time sector due to the limited range of local times sampled by the DMSP orbits. Therefore these results do not imply that the field models are too stretched compared to a growth phase field at midnight. Rather we suspect that in order to better represent the conditions at midnight the modelers may have made the models too stretched at other local times.

5. CONCLUSIONS

We have compiled a set of 102 conjunctions between one of three low-altitude DMSP satellites and one of two geosynchronous satellite using an algorithm that compares the field-aligned electron energy spectra measured at each location. Excellent spectral matches can be found for a subset of nominal conjunctions. Those conjunctions that meet our spectral matching criteria provide a sensitive and field model-independent determination of the magnetic footpoint of geosynchronous orbit.

While our study only tests the magnetic mapping between geosynchronous orbit and the auroral zone we find that it is generally consistent with the "Kiruna Conjecture" that auroral substorms are magnetically connected to the equatorial magnetosphere in the region between approximately 6 and 10 R_E. However, we also found that there can be considerable variation in the magnetic mapping and that statistically the uncertainty in the magnetic mapping predicted by magnetic field models is approximately $\pm 3°$. Only about 25-30% of the time did the field model predict the conjunction to within $\pm 1°$ and as much as 20% of the time the field model could be off by more than $\pm 5°$. Surprisingly, we found that none of the five field models tested here performed significantly better than any of the other models.

We also found that the footpoint of geosynchronous orbit varies over more than 10° of magnetic latitude. This is a larger range of latitudes than any of the field models tested can accommodate. This suggests that the next generation of magnetic field models should allow a greater range in the amount of stretching that they allow. However, we also found that all the field models were, on average, too stretched compared to the measured footpoints.

In the future we intend to both extend the database of measured magnetic conjunctions and to include more magnetic field models. Applying the same test to new magnetic field models should help determine if progress is being made in their development. We also intend to apply the technique to other spacecraft to extend the coverage in local time and in L-shell.

ACKNOWLEDGMENTS

We are grateful to P. T. Newell for providing the DMSP data and to the US Department of Energy Office of Basic Energy Science for financial support.

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